Structure Dynamics, Vortex Dynamics and Fluid Loading for Structures in Waves and Currents

Charles H.K. Williamson
Cornell University
252 Upson Hall
Ithaca, NY 14853
phone: (607) 255-3838 fax: (607) 255-1222 e-mail: cw26@cornell.edu

Award #: N00014-95-1-0332

LONG-TERM GOALS

The long-term goals of the research are to investigate the important mechanisms involved in the interaction of current with axisymmetric or cylindrical bodies, which are tethered or free to respond to the fluid forcing. We intend to undertake studies that measure in-line and transverse dynamics and forces, wake vortical motions, and signatures of such bodies undergoing vortex-induced vibrations. Our goal is also to investigate the individual and combined effects of orbital motions and amplitude attenuation with depth on the vortex motions and fluid loading on cylindrical structures in waves.

OBJECTIVES

The objectives of this program are firstly to investigate the response and forcing on elastically mounted bodies (cylinders) in a current, representing one case of a tethered structure in the ocean. We intend to understand resonance phenomena, and the relation between forcing and wake-vortex dynamics. A second component is the study of the dynamics of tethered bodies (spheres) in currents. This objective is to investigate the possible existence of periodic oscillation modes, the interaction between transverse and in-line vibrations, and the relationship between the dynamics, the forcing and the wake vortical dynamics/signatures. A third component of the program involves the study of periodic or transient vortex patterns, which can give rise to periodic or intermittent force fluctuations, for both vertical and horizontal cylinders in waves. In the case of the vertical cylinder, we shall understand fundamental aspects of this problem by utilizing a novel "oscillating pendulum" experiment to independently vary amplitude and (spanwise constant) amplitude gradient, while decoupling these effects from the orbital motions. We further intend to extend our study to the case of wave loading on a vertical cylinder. In the case of the horizontal cylinder under waves, we will understand the fundamentals of this problem by translating a cylinder in elliptic orbits in our "tailor-made" Computer-controlled Towing Tank.

APPROACH

The approach of the research is primarily experimental in nature, but will involve analysis, and possibly computations. We are presently continuing to use our new facility, the Cornell-ONR Water Channel, for the primary experiments involving vortex-induced vibrations. We will also be continuing to utilize the computer-controlled X-Y Towing Tank for detailed visualization and force measurements for bodies in steady/unsteady motion. Use is also made of several of our Wind tunnels to extend the parameter range of some of our tethered bodywork. Techniques have been brought to bear on these problems, including Digital-Particle-Image-Velocimetry (DPIV), force measurements (using two force balances), and Laser-Induced-Fluorescence (LIF) visualization.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **1998**	2. REPORT TYPE	3. DATES COVERED **00-00-1998 to 00-00-1998**

4. TITLE AND SUBTITLE **Structure Dynamics, Vortex Dynamics and Fluid Loading for Structures in Waves and Currents**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Cornell University,252 Upson Hall,Ithaca,NY,14853**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002252.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

WORK COMPLETED

Current-Structure Interactions. We are continuing to use the experimental arrangements set up during the course of this research program for the tethered-sphere dynamics problem, and for the cylinder vortex-induced vibration problem. Initially, both of these experiments were being conducted in our Water Channel, although we have also extended our scope of study to include several wind tunnels, to enlarge our parametric range in the problems.

Wave-Structure Interactions. We have incorporated into our experimental arrangements in the Computer-Controlled XY Towing Tank, a force balance system, which is being used to determine lift and drag forces on both projects in this facility; namely, the elliptic orbit problem and the oscillating pendulum problem.

Our DPIV system for determining vorticity is being used to determine velocity and vorticity fields in all of these projects. Our increased image resolution this past year has been instrumental in enabling us to achieve several new results. We have set up a higher-resolution CCD Camera system over the past year for use in the flow visualizations and the DPIV measurements, which can be mounted on a moving or fixed reference frame. We have been measuring forces simultaneous with flow visualizations and DPIV measurements.

In our study of the tethered sphere in a current, we have continued to experiment with spherical bodies, of varied mass ratios M^*, and varied normalized tether lengths, L^*. We have tethered our spheres to the bottom of the Water Channel, with pre-stretched ultra-thin wires, and we have also used a similar (but inverted) set-up in wind tunnels for spheres heavier than the surrounding fluid ($M^*>1$). Our approach to measuring in-line and transverse displacements of the sphere incorporates the use of advanced technology of image processing, which allows real-time X-Y position information.

In our study of the hydroelastic cylinder, we are continuing to utilize an arrangement, which, like the above sphere problem, has minimal intrusion. We have been able to measure forces simultaneous with the cylinder displacements and the DPIV technique, using the tailor-made force balance. We have also been using LIF Dye visualizations to infer basic vortex motions.

RESULTS

In our experiments concerning vortex-induced vibration of cylinders at extremely low mass and damping, we have set up a system which has a specific mass of around 1% of that used in the classical work of Feng (1968). Under these conditions, the synchronization regime extends to around four times the extent of normalized velocity as found by Feng, and with a large amplitude in excess of 1D. Three branches of amplitude are found within the synchronization regime, in contrast to the two branches found for high mass-damping in the Feng experiments. These branches are denoted as the initial excitation regime, the upper branch, and the lower branch.

There are distinct differences in the character of mode transitions, as follows: As normalized velocity is increased, there is a *hysteretic jump* from the initial excitation region to the upper branch (see Figure 1). Whereas, the jump from the upper to lower branch involves an *intermittent switching*, which we illustrate by plotting the instantaneous phase between lift force and displacement using the Hilbert Transform (see Figure 2). These low mass-damping jump phenomena are clearly different from the high mass-damping experiments of Feng.

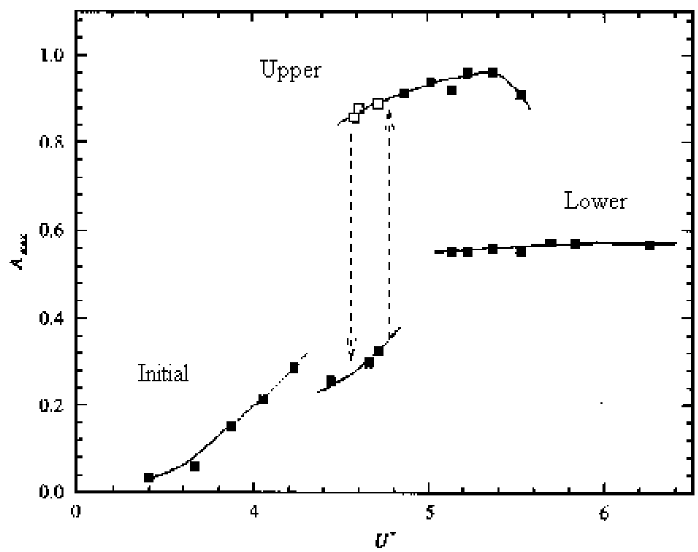

Figure 1: Amplitude (A) versus normalized velocity (U*).

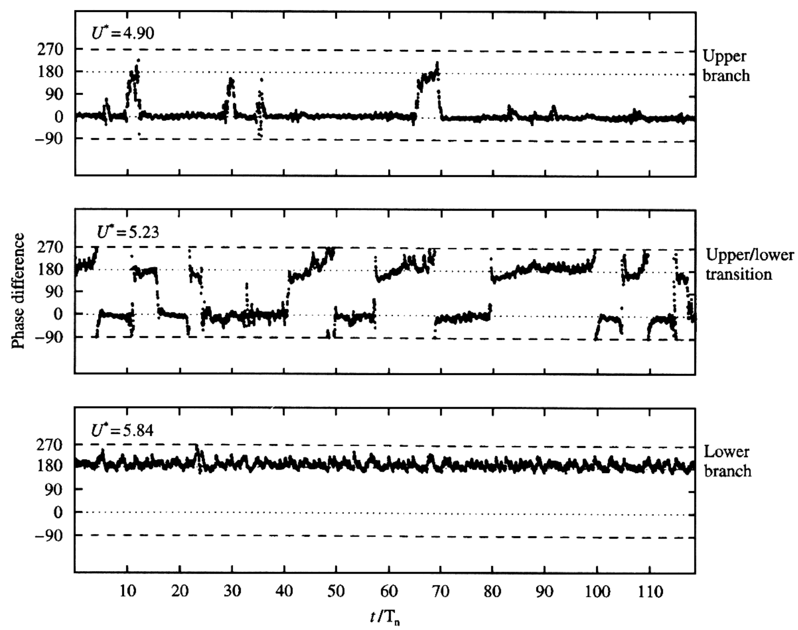

Figure 2: Intermittent switching between upper and lower branches, demonstrated by Phase versus time plots using Hilbert Transform.

Contrary to classical "lock-in", whereby the oscillation frequency is usually presumed to match the structural natural frequency, we find that the oscillation frequency increases markedly above the natural frequency, through the excitation regime. This is one of the first demonstrations of this effect, and it agrees with similar phenomena for the tethered sphere problem. However, it is found to correspond well with the recent results from Tony Leonard's group at Caltech (Mo Gharib et al.), and is consistent with predictions one might make from forced oscillation experiments based on Sarpkaya's extensive papers on the subject (for example, Sarpkaya, 1995).

Evidence at present suggests that the largest amplitude that can be attained by a vibrating cylinder is in excess of the previous measurements, if one reduces mass and damping to extremely low levels, and

lies above the collapsed data of the classical "Griffin plot" (amplitude versus mass-damping plot, recently updated by Skop and Balasubramanian, 1997).

Our measurement of vorticity using DPIV, during free vibration, is one of the first such experiments to be done for a hydroelastic cylinder (along with Rockwell's hydroelastic body in waves). We confirm the existence of *repeatable* vortex patterns corresponding to the "2P" mode for the lower branch, and the "2S" mode for the initial regime (the patterns were originally defined in this manner in Williamson and Roshko, 1988, from forced oscillations). The question of the existence of the 2P mode as being simply a *transient* mode has been often raised recently, although we find, in these experiments, repeatability of the 2P mode indefinitely.

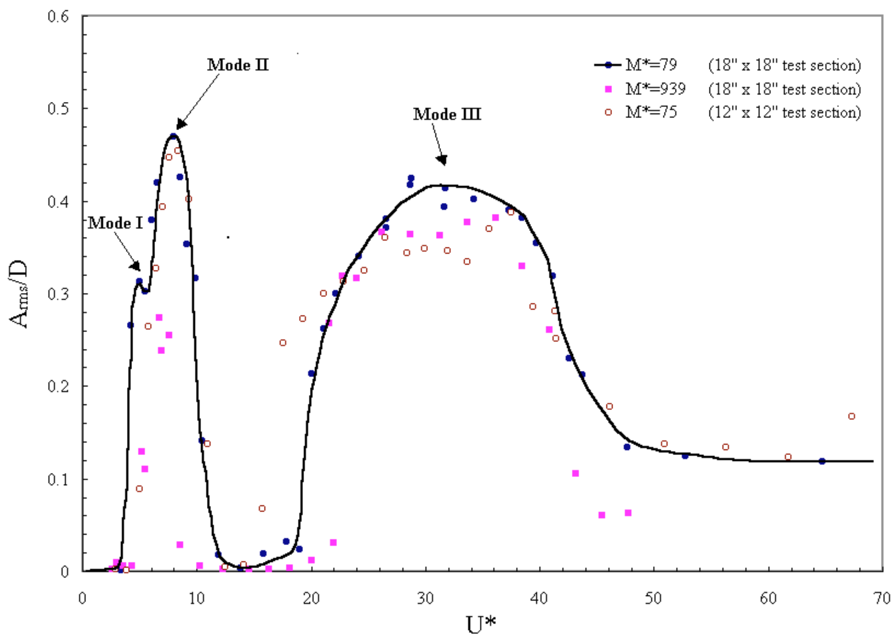

Figure 3: Amplitude response of a tethered sphere in a free stream.

In our experiments concerning the tethered sphere in a current, we have been excited to find enormous synchronization regimes, whose extent (as measured by range of normalized velocity) is beyond the limits of our facilities for low mass ratios (of order 0.1), but is limited to U*~12, for high mass ratios (of order 100). (U* = U/fnD, where U = free stream velocity, fn = natural frequency, D = diameter). This is consistent with some of our cylinder experiments. However, what has come as a complete surprise, through the fact that we have conducted experiments in different mediums, allowing a very large range of mass ratios = 0.1 - 1000, is that three periodic modes appear in the response. The first two modes (see Figure 3) correspond with the "2S" and "2R" modes (the 3D analogues to the 2S and 2P modes of the cylinder problem, cited last year), and occur for velocities between about U*=5-10, i.e., near the classical resonance conditions. The third mode, on the other hand, is found to be very broad, extending from U*=20-40, with a large amplitude response, and whose physical origin is presently the subject of intense work. The P.I. was extremely skeptical of its existence, despite his research team's insistence, but further checks at different mass ratios (of order 100 and 1000), and in different-sized wind tunnels, confirms this wholly unexpected new result.

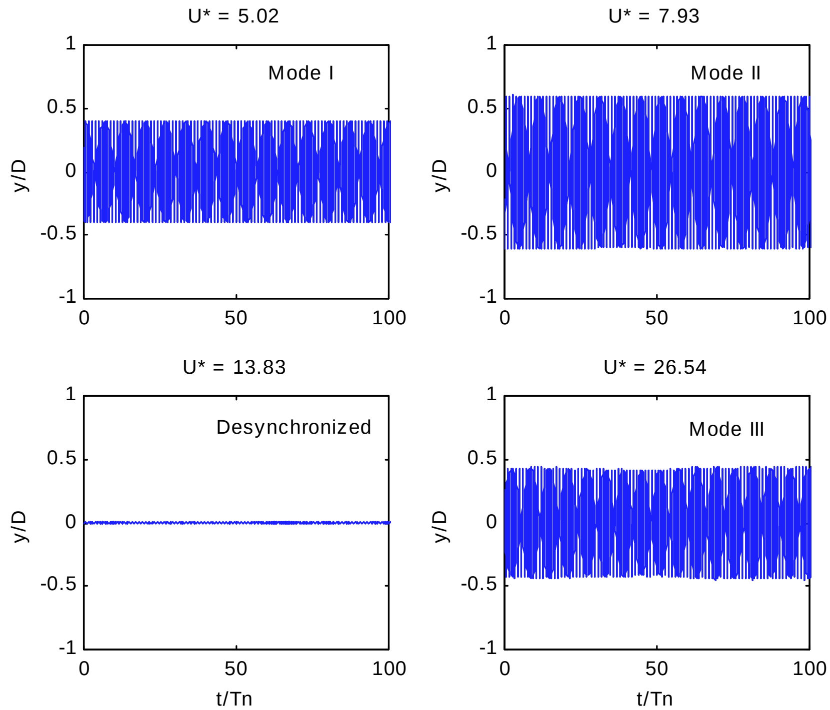

Figure 4: Demonstration of the highly-periodic sphere response for Modes I, II and III.

Parts of this work has been presented at the Bluff Body Wakes and Vortex-Induced Vibration Conference (Washington, DC, USA) in 1998. The PI with Co-Organizer Peter Bearman of Imperial College, London, organized this Conference, spanning three days with 60 seminars. The Office of Naval Research supported the publication of color Proceedings, which would not otherwise have been available. Our work on vibrations of cylinders and spheres has also formed the basis of papers in *Journal of Fluids and Structures* (3 papers) and *J. Wind Engineering and Industrial Aerodynamics* (4 papers), with upcoming submissions to *JFS* and *Journal of Fluid Mechanics*.

IMPACT/APPLICATIONS

These fundamental studies of current-structure interaction have direct application to the dynamics, wakes and surface signatures of tethered or free near-surface bodies. Our investigations of the tethered-body problem show that proper account of the unsteady dynamics of such tethered structures is very important to a correct prediction of the wakes and signatures. The work here shows 100% magnification factors on the induced drag and tether angle, due to body vibrations.

An important practical implication is given by the enormous range of normalized velocity over which synchronized self-excited motions are found. For low mass ratios, we have measured no limit to the regime of synchronization within the velocity range of our facilities. While for high mass ratios, we have discovered 4 distinct modes of large-amplitude vibration, yielding significant response up to at least a normalized velocity of U*=300 (noting that the classical resonance in these systems occurs for U*~5).

We have set up a vortex-induced vibration experiment involving an elastically mounted cylinder, with extremely low mass and damping. The frequency response at low mass-damping, and the form of the amplitude response, as a function of incident flow velocity, has applications to vortex-induced

vibrations of structures in a current. The question as to how much a structure will move, for given structural parameters is perhaps the most basic and practical question one might pose, and though a simple question, the dynamics are complex and rich in phenomena. The question as to how much force is exerted (coefficients up to at least 5.0 - 6.0, for example) is also a most basic practical question for vibrating structures. Both of these apparently simple questions provide a strong driving force in our ongoing work.

The fundamental studies of wave-structure interaction will have application to the fluid loading on ocean structures. Our proposed work is to understand the role of the vortex dynamics on fluid loading for vertical as well as horizontal cylinders in waves. Our Elliptical orbit studies, involving both force measurements and flow visualizations, show that there exist vigorous vortex dynamics in the wake of a body that undergoes orbital (even circular) motions, suggesting that one should expect high frequency fluid forcing on the body. It is particularly of interest that we have shown the existence of periodic forcing at multiples of the wave frequency that would have an impact on the design of ocean structures.

In our “Oscillating Pendulum” study, we are investigating how the spanwise gradient of oscillation amplitude past a cylindrical body affects the vortex dynamics and forces. We have found distinct force resonances on such an “oscillating pendulum” despite the existence of the amplitude gradient and of the corresponding variation of vortex dynamics along the span.

TRANSITIONS

It is our intention to verify the present phenomena and data at large-scale, for both the current-structure and wave-structure interactions problems.

RELATED PROJECTS

Substantive interactions have been made, and will be made, with several other groups studying vortex-induced vibration and wakes e.g., involving visits/seminars or collaborative work (Lehigh; MIT; Oxford; University Sao Paolo, Brazil; Monash University, Australia), and involving directly-relevant conferences (BBVIV (ASME-sponsored) Conference Washington June 1998) where related projects can be discussed at length. Interactions concerning vortex-induced vibrations with CSIRO and Monash University in Melbourne, Australia are ongoing.

PUBLICATIONS

Williamson, C.H.K., 1997: “Recent developments concerning vortex dynamics and instabilities in wakes”, Invited Review in special edition on “Bluff Body Aerodynamics and Applications” of *J. Wind Engin. and Industrial Aerodynamics*, 69-71, 3-32.

Khalak, A. and Williamson, C.H.K., 1998: “Forces, dynamics, and mode transitions for elastically-mounted structures with very low mass and damping”, submitted to *Journal of Fluids and Structures*.

Williamson, C.H.K. and Brown, G.L., 1998: “A series in $1/\sqrt{Re}$ to represent the Strouhal-Reynolds number relationship for the cylinder wake”, accepted for *Journal of Fluids and Structures*.

Leweke, T., Provansal, M., Miller, G.D. & Williamson, C.H.K., 1997: "Cell formation in cylinder wakes at low Reynolds numbers", *Physical Review Letters*, 78, 1259.

Leweke, T. and Williamson, C.H.K., 1997: "Three-dimensional instabilities in wake transition", *European Journal of Mechanics - Fluids*., In Press.

Leweke, T. and Williamson, C.H.K., 1998: "Cooperative elliptic instability in a vortex pair", *Journal of Fluid Mechanics*, 360, 85.

Leweke, T. and Williamson, C.H.K., 1998: "Long wave instability in a vortex pair", submitted to *Journal of Fluid Mechanics*.

Prasad, A. and Williamson, C.H.K., 1997: "The instability of the shear layer separating from a bluff body", *Journal of Fluid Mechanics*, 333, 375.

Khalak, A. and Williamson, C.H.K., 1997: "Fluid forces and dynamics of a hydroelastic structure with very low mass and damping", *Journal of Fluids and Structures*, 11(8).

Prasad, A. and Williamson, C.H.K., 1997: "Three-dimensional effects in turbulent bluff body wakes", *Journal of Fluid Mechanics,* 343, 235.

Khalak, A. and Williamson, C.H.K., 1997: "Investigation of the relative effects of mass and damping in vortex-induced vibration of a circular cylinder", *J. Wind Engin. and Industrial Aerodynamics*, 69-71, 341.

Govardhan, R. and Williamson, C.H.K., 1997: "Vortex induced motions of a tethered sphere", *J. Wind Engin. and Industrial Aerodynamics*, 69-71, 375.

Prasad, A. and Williamson, C.H.K., 1997: "A method for the reduction of bluff body drag", *Journal Wind Engin. and Industrial Aerodynamics*, 69-71, 155.

Williamson, C.H.K. and Govardhan, R., 1997: "Dynamics and forcing of a tethered body in a fluid flow", *Journal of Fluids and Structures*, 11, 293.

Prasad, A. and Williamson, C.H.K., 1997: "Three-dimensional effects in turbulent wakes", *Experimental, Thermal and Fluid Science*, 14, 9.

Leweke, T. and Williamson, C.H.K., 1998: "Short wave instability in vortex pairs and in wake vortices", 13th Australian Fluid Mechanics Conference, 13-18 Dec. 1998, Monash University, Melbourne, Australia.

Govardhan, R. and Williamson, C.H.K., 1998: "Dynamics and instability modes of a tethered body", Paper Proceedings of Bluff Body Wakes and Vortex-Induced Vibration, (Ed: P.W. Bearman and C.H.K. Williamson) 21-25 June 1998, Washington, DC, USA. Paper #8.

Leweke, T. and Williamson, C.H.K., 1998: "Physical basis of instability modes in transition", Paper Proceedings of Bluff Body Wakes and Vortex-Induced Vibration, (Ed: P.W. Bearman and C.H.K. Williamson) 21-25 June 1998, Washington, DC, USA. Paper #32.

Braza, M., Persillon, H. and Williamson, C.H.K., 1998: “Three-dimensional vortex dynamics and dislocations, utilizing DNS, in wake transition”, Paper Proceedings of Bluff Body Wakes and Vortex-Induced Vibration, (Ed: P.W. Bearman and C.H.K. Williamson) 21-25 June 1998, Washington, DC, USA. Paper #34.

Williamson, C.H.K., Peter, M., Hess, P. and Govardhan, R., 1998: “Fluid loading and vortex dynamics resonances on structures in waves”, Paper Proceedings of Bluff Body Wakes and Vortex-Induced Vibration, (Ed: P.W. Bearman & C.H.K. Williamson) 21-25 June 98, Washington, DC, USA. Paper #18.

Govardhan, R. and Williamson, C.H.K., 1998: “Modes of vortex-induced vibration of a tethered sphere”, Bull. American Physical Society, 43, ---.

Williamson, C.H.K., Govardhan, R., Peter, M., Hess, P., Brunot, A. and Tangprasert, S., 1997: “Vortex dynamics and force resonances around structures in oscillating flows”, Bull. American Physical Society, 42, 2177.

Leweke, T. and Williamson, C.H.K., 1997: “Three-dimensional instabilities in wake transition”, Bull. American Physical Society, 42, 2133.

Williamson, C.H.K. and Leweke, T., 1997: “Modes of vortex instability and ‘vortex dislocations’ in wake transition”, *Dynamics and Statistics of Concentrated Vortices in Turbulent Flows*, pp. 90, 24-27 June 1997, IRPHE, Marseilles, France.

Williamson, C.H.K. and Leweke, T., 1997: “Distinct modes of small-scale instability in wake transition”, *11th Symposium on Turbulent Shear Flows*, Vol. 2, pp. 17.12 - 17.17, 14-16 August 1997, Grenoble, Switzerland.

Leweke, T. and Williamson, C.H.K., 1997: “Internal deformations of interacting vortices”, 3rd European Fluid Mechanics Conference, 15-18 Sept.1997, Gottingen, Germany.